THE FLIGHT PERFORMANCE OF THE GALILEO ORBITER USO

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Abstract

Radiometric tracking Doppler measurements of the signal transmitted by the Galileo spacecraft using an Ultra--Stable Oscillator (USO) as a frequency reference have been acquired by antennas of the NASA Deep Space Network (DSN) between Dec. 1989 and Nov. 1991. These measurements serve two purposes; 1) the scientific investigation of the gravitational redshift phenomenon as the spacecraft moves in and out of the gravitational fields of massive bodies in the solar system, as predicted by Einstein's theory of general relativity, and 2) engineering evaluation of the Uso frequency anti frequency stability for calibration purposes, and to evaluate the health and performance of the USO. These calibrations serve as a baseline for Radio Science experiments, such as the Redshift Observation and occultations of Jupiter and its satellites.

The USO is a dual oven-controlled oscillator with an AT-cut quartz crystal (SiO_2) resonator. The output frequency of 19.124980 MHz is multiplied by 120 to produce the transmitted signal frequency (~2.29 GHz).

There were 82 data acquisition passes conducted between launch (oct.. 1989) and Nov. 1991. Each pass consisted of about two hours of Doppler data sampled at one per see, received by the DSN antennas using Hydrogen-masers as frequency and timing references. The Doppler were converted into estimates of spacecraft transmitted frequencies and frequency residuals after removal of the spacecraft. trajectory and other effects.

The USO-referenced frequencies showed a significant. positive logarithmic increase shortly after initial turn-on, which is probably due to the liberation of contamination on the crystal vibrator surfaces acquired during the long period of inoperation prior to launch. A least-squares fit. to an aging model (combination logarithmic curve and linear drift) was applied to the estimated frequencies of the 76 passes acquired during the first in-flight USO on-off cycle (Dec. 1989 to Aug. 1991). The residuals showed a large systematic variation shortly after initial turn-on. Since the aging behavior during this period is complex, the first twelve passes were removed, and the model was fit to the remaining 64 passes. The resulting post--fit residuals showed no significant systematic variation. It is believed that the variations of the 17 mHz rms residual scatter are due to the random walk of the USO or possible unknown mismodeling. It took a little over a year of continuous operation before the USO reached its linear aging realm (--5.6 x 10-12/day). The USO was powered-off and back on in Aug. 1991 with no adverse effect on its performance.

The average Allan deviations at 1-S and 10-s correlate well with spacecraft range, and fall as 7". This is consistent with white PM noise dominating at these time scales due to the low SNR's expected from using the Low Gain Antennas. The Allan deviations at 100-s and 1000-s agree with pre-flight USO stability results at these time scales. The Galileo USO appears to be healthy and functioning normally.

1. Introduction

This is an article on the efforts to characterize the instrument used for the Galilee) Radio Science investigation. It discusses the performance of the Ultra Stable Oscillator (USO), which, when the spacecraft. and ground elements of the instrument are configure] in the one-way mode, is the limiting error source observed in the received Doppler data at time intervals where there is sufficient signal power.

Galileo was originally scheduled to be launched in May 1986, but was delayed due to the Challenger accident. Galileo was launched on Oct. 18, 1989 and the USO was turned-on on Dec. 5, 1989. Galileo acquired gravity assists from Venus (Feb. 1990) and Earth (Dec. 1990, Dec. 1992) and will go into orbit around Jupiter in Dec. 1995. Between Dec. 1989 and Nov. 1991, 94 passes have been scheduled for two-hour data acquisition periods of the Galileo spacecraft where the USO was the signal source. However, not all scheduled passes resulted in valid data; twelve passes were lost for various reasons (six were aborted after a spacecraft safing anomaly early in 1990, four were lost due to a crashed sequence in March-April 1991, and two were lost due to unrecoverable data problems). Data for the remaining 82 passes were acquired by the DSN and delivered to the Galileo Radio Science Team (RST) for analysis in the form of Archival Tracking Data File (ATDF) tapes. Estimates of the spacecraft transmitted frequency and frequency stability were made for the 82 passes conducted during these first two years of cruise. Each pass consists of about two hours of doppler data sampled at 1/s, and Hydrogen-masers served as the frequency and timing references. 'l'he received doppler data were converted into estimates of spacecraft transmitted frequencies and frequency residuals after accounting for spacecraft trajectory and other effects.

II. Purpose

The U.SO-referenced data were acquired for two purposes; 1) the scientific investigation of the redshift phenomenon: the frequency shift as the spacecraft moves in and out of the gravitational fields of massive bodies in the solar system as predicted by Einstein's theory of general relativity, and 2) engineering evaluation of the USO frequency and frequency stability for calibration purposes and to evaluate the health and performance of the USO. These calibration data serve as a baseline for Radio Science experiments such as the Red Shift Observation, Solar Corona Experiment, and occultations of Jupiter and its satellites. This article will focus only on the engineering aspects of the USO data. The scientific results are discussed in [1). For discussions of the expected scientific results of the Galileo Radio Science investigations, the reader is referred to [2,3].

'l'he goal of the USO analysis is, thus, to establish the Use-referenced spacecraft transmitted frequency and the frequency stability associated with it and to build a database containing the statistics and all parameters relevant to the measurements.

III. Spacecraft Configuration

The Galileo spacecraft configuration for these Radio Science tests is the normal cruise configuration, with the exception of a command which enables the USO to be the radio downlink reference; this is the mode required for the redshift experiment and future occultation investigations. No configuration changes such as changing the telemetry modulation index were expected during a pass. The majority of the tests were performed on a "quiet" spacecraft where no maneuvers or other motion was permitted to occur.

'l'he USO, a science payload instrument integrated with the spacecraft's telecommunications subsystem, was manufactured by Frequency Electronics Inc., New York between 1975 and 1976. The USO which resides in the Radio Frequency subsystem (RFS) of the Galileo orbiter is serial number #4, from the same lot as the USOS flown on Voyagers 1 and 2. The Voyager 1 USO failed in Nov. 1992 (after fifteen years of continuous service), engendering concerns about the survival lifetime of the Galileo USO. The USO is a dual oven controlled device with an AT-cut quartz crystal (SiO_2) resonator. The design output frequency is 19.125000 MHz. When the USO is the downlink signal source, it drives the S-band exciter. The output frequency is multiplied in the transponder by a factor of 120 to produce the 2.29 GHz transmitted signal. The S-band Traveling Wave Tube Amplifier (TWTA) amplifies the signal it receives from the S-hand exciter to either one of two power levels; the high-power mode (27 watts) or the low power mode (9 watts). The TWTA has routinely been configured to the high-power mode. 'l'he S-band TWTA provides the amplified RF output to the HGA/LGA transmit switch of the S-band antenna switch, which connects the outputs of the S-band TWTAs to either the HGA or the LGA. If the HGA is ever to be successfully deployed, an

X-band (8.4 GHz) transmitted signal will also become available and its frequency will be 11/3 of the S-band signal frequency.

All of the data acquired were at 2.3 GHz and Right Circularly Polarized. The signal was transmitted from the spacecraft via either LGA-1 or LGA-2 (Low Gain Antennas). LGA-1 is located on the spacecraft spin-axis in front of the HGA tip sunshade. LGA-2 is located on a boom 3.58 m away of the spin axis, and is pointed in the direction opposite that of HGA and LGA-1. Both LGAs work at 2.3 GHz only. LGA-2 was utilized for the period right after launch and the period right after the Earth 1 encounter. The time periods of the spacecraft LGA configuration for the data set analyzed in this article are given below;

10/18/89	to	03/15/90	LGA-2
03/15/90	to	12/08/90	LGA-1
12/08/90	to	01/31/91	LGA-2
01/31/91	to	11/30/91	LGA-1

The Galileo spacecraft is a spin-stabilized spacecraft which rotates at about three rpm.

IV. Ground Data System Configuration

The DSN configuration was also that of normal cruise tracking. The radio metric data were sampled at a rate of one per second using a loop filter bandwidth of 10 Hz. For all of the passes, hydrogen-masers were the frequency and timing references at the ground stations. The overall stability of the ground system (frequency reference, receiver, cables, etc.) is expected to be about 1×10^{-15} at 1000 sec, which is far more stable than the USO.

The following data products are received for each pass; an ATDF tape containing the closed-loop Doppler data, a pass folder from the DSN containing copies of frequency predictions, operator logs and related material, and a spacecraft trajectory vector file from the Galileo Navigation Team.

V. Analysis Software and Techniques

The analysis was performed on the Radio Science Support System RODAN (Radio Occultation Data Analysis Network) computer which includes a Prime 4050 computer, a Floating Point Systems (FPS) array processor, two magnetic tape drives and other peripherals. The system is accessible by a set IBM Ps/2 terminals as well as two Sun workstations.

Although the analysis tools used for this work were inherited from the Voyager Project, there were enough differences in configuration and procedures in the Galileo Project that non-trivial modifications were made to the software and techniques. The analysis software was upgraded to estimate more accurately the spacecraft transmitted frequency and the frequency residuals used for the stability analysis, including installation of code to model the effects introduced by a spinning spacecraft.

The data were processed by the STBLTY software program set. The functions of each of the component programs (see Fig. 1) are described below.

The program OCEP reads the doppler counts and doppler extractor reference frequency from the input Archival Tracking Data File (ATDF) tape, converts these to sky frequencies, and writes the time-tagged frequency data and related information to the F50 file.

The program GETTRAJ reads the spacecraft state vectors from the Navigation Team provided Celestial Reference Set (CRS) trajectory file, performs vector manipulations and light-time solutions, and writes the F45 output file containing the time-tagged spacecraft position and velocity vectors relative to the sun and the observing ground station. Details of the orbit determination solutions determined by the Galileo Navigation Team used to generate the trajectory are given elsewhere [4].

The program RESID reads the output files of the two previous programs (F50 sky frequencies and F45 trajectory vectors). Mode 1 sky frequencies are estimated from the trajectory vectors, and are corrected for troposphere, spacecraft spin, gravitational redshift and, if applicable, the spinning off-axis LGA-2 antenna induced doppler signature. The spacecraft transmitted frequency is estimated at the time tag of the first data point, and the frequency residuals are computed by differencing the observed sky frequencies from the estimated sky frequencies for each data point. The troposphere model is a simple zenith path delay translated to the line-of-sight elevation angle. A spacecraft-spin model correction is applied to the estimated downlink frequency and residuals. The magnitude of this correction depends upon whether the spacecraft was in all-spin mode (0.0481 Hz) or dual-spin mode (0.0525 Hz). The sign of this correction depends upon whether the signal source was LGA-1 or LGA-2. This program writes the residual frequencies and related information to the F52 output file.

Relativistic effects, including the gravitational redshift, are modeled in the analysis, and removed from the data. The results of the scientific analysis of these effects, the first test of the solar redshift with an interplanetary spacecraft, indicates that the total frequency variation as predicted by general relativity has been verified to an accuracy of 0.5% and the solar gravitational redshift to 1% (Ref. 1). Therefore, it can be stated with a reasonable degree of confidence that these effects have been removed to the stated accuracies.

The program STBLTY reads the F52 file, computes and applies a bias correction to the spacecraft transmitted frequency estimate relative to the center of weight of the residuals over the pass, and computes phase, Allan deviation, frequency and phase power spectral densities (PSDs), other relevant statistics and writes selected information for the current pass onto a data base summary file. This program also produces plots of relevant data quantities.

Once all of the USO passes have been processed through the above programs, the data base file will contain a set of records for each processed pass. This file is then processed through the programs FITUSO and USOSMRY.

The program FITUSO reads the frequencies from the data base, and fits and removes an aging model. The resulting post-fit residuals are written onto a previously blank field of the data base. The user can specify how many passes to skip, how many passes to accept and where the break between logarithmic and linear aging behavior occurs.

The program USOSMRY reads the USO data base and displays graphically any requested quantities from a menu of available data types.

VI. Analysis Results

A. General Single Pass Results

Eighty-two of ninety-four scheduled USO-referenced data acquisition passes were processed through the STBLTY program set. Each pass was typically two hours in duration. All data processed were closed-loop data acquired by the Deep Space Stations sampled at 1/s. Table 1 displays the year, day number, UTC start time, UTC end time, DSS station ID, signal level (AGC), and estimated spacecraft transmitted frequency for each pass. Fig. 2 displays a typical plot of the residuals after the removal of the spacecraft trajectory, the gravitational redshift, a simple troposphere model, and the effect of the spacecraft spin when LGA-1 is the signal source. Fig. 3 displays the frequency residuals after every 60 points have been averaged, allowing long period trends to be easily examined. Fig. 4 displays the reconstructed phase for the residuals of Fig. 2. Fig. 5 is the log of the Allan deviation for the residuals of Fig. 2. Figs. 6 and 7 display the logs of the frequency spectral density and phase spectral density, respectively, for the residuals of Fig. 2. The spikes at about 0.05 Hz are related to the 3 rpm spacecraft spin.

B. LGA-2 Induced Spin Doppler Example

When LGA-2 is the signal source, there is a significant sinusoidal signature present in the received doppler due to LGA-2 being mounted on a boom located 3.58 meter from the spacecraft spin axis. Fig. 8 displays a typical plot of frequency residuals for a pass where LGA-2 was used, after the trajectory and other effects were removed. Fig. 9 clearly illustrates the sinusoidal signature for a selected 200 sec period.

In order to remove this signature from the data, a three-parameter sinusoidal model was iteratively fit to the Doppler residuals of Fig. 8. This model includes an amplitude, a frequency and a phase offset. After the model was successfully fit and removed, the resulting "post-fit" residuals (see Fig. 10) yielded Allan deviations consistent with those of LGA-1 passes, suggesting that the three-parameter sinusoidal model is sufficient for removal of the spin-induced Doppler signature.

For three passes where LGA-2 was the signal source 91-01-14 (91-014), 90-01-09 (90-009) and 90-12-10 (90-345), dynamic activity occurred on-board the spacecraft which introduced phase shifts into the data. The result is that the fit of the sinusoidal model failed to remove all of the induced off-axis LGA-2 Doppler signature, resulting in residuals as exemplified in Fig. 11 for pass 91-014. In this specific case, tape recorder motion was known to occur, where the envelope changes in Fig. 11 correlate with the tape recorder start and stop times. Fig. 12 illustrates the resulting degradation to the Allan deviation (compare with Fig. 5). Pass 90-345 occurred after the Earth I flyby where several activities occurred on-board the spacecraft which introduced dynamic motion. Commands which introduced dynamic motion on the spacecraft also occurred during pass 90-009. In these cases, the dynamic activity was assumed to be symmetric about the center of weight of the spacecraft and thus appeared not to have biased the estimated spacecraft. transmitted frequencies which arc determined at the first data point, and then translated to the center of weight of the residuals over the full data span. The Allan deviations for these passes were however degraded.

C. Solar Interference Example

Fig. 13 displays the residuals for pass 91-03-05 (91-064) where several solar disturbances occurred during that day including the period of the data acquisition. The degradation in the observed Doppler noise measurements from the closed-loop system are consistent with those expected from solar interference (R. Woo, private communication) . 'l'his was the only pass in this data set where this behavior was observed. The estimated spacecraft transmitted frequency appears reasonable, however, the Allan deviations were degraded as expected.

D. Stability Analysis Results

The Allan deviation is the recommended measure of oscillator stability for time domain signal processing. The Allan deviations are displayed in Figs. 14-17 for 1, 10, 100 and 1000 sec time intervals, respectively. Outlier passes which contain degraded data have been removed. Outlier passes include a) the three passes where dynamic events were known to occur on the spacecraft 900109 (90-009), 901210 (90-345), and 910114 (91-014), b) the suspected solar interference pass 910305 (91-064), c) three passes where the cause of the degradation is not known, but is possibly due to ground equipment problems 900330 (90-089), 911019 (91-292) and 911130 (91-334), and d) the first two passes after initial turn-on (89-341, 89-350) where the significant increasing frequency dynamics adversely dominated the Allan deviation measurements at 1000 sec.

The measured means and errors of the Allan deviations are given in Table 2 for each time interval (outlier passes were removed as well as three passes where there were insufficient data to estimate Allan deviations at 1000 see). The pre-flight Al Ian deviation measurements of the Galileo USO for these time intervals are also presented in Table 2. The pre-flight measurements were performed at the JPL Hydrogen Maser Test Facility on May 1, 1980 [5]. Fig.)8 is a plot of the averages of the measured flight Allan deviations with the pre-flight measurements superimposed.

For 1 and 10 see, the measured flight Allan deviations significantly exceed the pre-flight Al Ian deviations. This was expected since it is known that wideband thermal system noise (white phase noise) dominates at these time intervals due to the low signal-to-noise ratios resulting from using Galileo's low gain antennas. The flight Allan deviations for individual passes agree with estimates derived from the measured signal levels, system noise temperatures (~20 K) and receiver bandwidth (10 Hz). The Allan deviations at 1 sec (Fig. 14) and 10 sec (Fig. 15) also correlate with spacecraft range (compare with Fig. 19). If the HGA ever becomes available, and if there is an opportunity to turn off the telemetry modulation to increase the signal strength, there will better visibility of the true USO performance at the l-see and 10-sec time intervals.

The average of the flight Allan deviations at 100 and 1000 sec agree with the corresponding pre-flight values in Table 2 and Fig. 18. This implies that the flight data are dominated by the true behavior of the USO at these time intervals. The apparent large scatter of the 100-sec (Fig. 16) and 1000-sec (Fig. 17) Allan deviations is in agreement with theoretical values using equations derived by Lesage and Audoin [6].

The hump at 70-sec in the pre-flight values in Fig. 18 has been attributed to the thermal oscill ation of the inner oven current driven by noise (G. Wood , private communication). The consistent behavior of the flight data between 100 s and 1000 s with the pre-flight. measurements at these time intervals implies that this effect is visible in the flight data. In the absence of this thermal cycling, one would then expect the Allan deviation behavior to be flat over these time scales, and thus be consistent with flicker frequency noise. The expected noise due to unmodeled medi a fluctuations lies well below this level at these time intervals.

The Allan deviation behavior for the flight data measurements can be broken down into several regions. The Allan deviation in the 1 to 10 sec region falls roughly as τ^{-1}, characteristic of white phase noise dominating at these time intervals. The uso behavior here is masked by this noise at these time scales. The behavior of the region from 100 to 1000 sec can be interpreted as being consistent with the known inner-oven thermal cycling effect being superimposed on a flicker frequency noise floor (using the pre-flight measurement information). Between 1000 sec to about 40000 see, one can assume a continuation of the flicker noise floor upon inspection of the pre-flight measurements and error bars.

E. Signal Levels

'The Galileo passes have relatively low signal levels which run from about -140 dRm shortly after launch and around Earth I flyby to as low as -170 dBm. The receiver threshold is typically about -176 dBm. As previously discussed, the Al Ian deviations derived from the measured signal levels using thermal noise theory are consistent with the measured Allan deviations at 1 and 10 sec. The signal level behavior also correlates well with spacecraft range (Fig. 19).

After correcting the received signal levels for receiver station antenna gain, space loss, spacecraft LGA antenna gain, and telemetry state carrier suppression, the resulting spacecraft transmitted power levels at the Radio Frequency Subsystem/Antenna interface of the spacecraft were computed. These mean values were in good agreement with the expected power levels, and were within the k nown calibration uncertainties at the ground stations.

F. Analysis of Spacecraft Transmitted Frequency Measurements

The frequency transmitted by the spacecraft was estimated for all 82 passes. Fig. 20 displays the USO-referenced spacecraft transmitted frequencies as estimated by STBLTY. Each point on the plot is the USO frequency estimated at the first time tag for that pass and then corrected to the center of weight of all of the residuals over that pass. The assigned uncertainties of the estimated frequencies run about 3 mHz and are dominated by the uncertainty inferred by not performing an ionosphere correction. The plot is annotated with the times the USO was powered on and off. The time axis is in days since Jan. 1, 1989. The USO was initially powered-on in flight on December 5, 1989 (DOY 339) . There was one instance of cycling the USO off (91-217) and then back on (91-228) in this data set.

A preliminary pass of a few minute duration was conducted shortly after initial turn--on on Dec. 5, 1989 (and after the inter-oven current was allowed to stabilize) in order to verify operation of the USO. Here the frequency was observed to be increasing at a very high rate, exhibiting dynamic behavior due to early impurity migration and/or stress relief resulting in the very poor stability expected shortly after turn-on. The fi rst valid USO pass was conducted on Dec. 7, 1989, several hours after initial turn-on.

Changes in the USO frequency with time are referred to as resonator aging. In general, the principle causes of aging are stress relief in the mounting structure of the crystal unit, mass transfer to or from the resonators surface due to adsorption or resorption of contamination, changes in the oscillator circuitry, and possibly changes in the quartz. [7]. Aging effects seen in this data set likely include surface liberation of impurities, impurity migration across and within the crystal, and linear aging (diffusion). The significant positive logarithmic increase i n frequency shortly after initial turn-on (see Fig. 20) is probably due to the liberation of contamination on the crystal resonator surfaces which were acquired during the long period of inoperation prior to launch (R. Sydnor, private communication) . The USO was powered off for much of the time 1986-1989 that the spacecraft was dormant on the ground prior to launch. The linear region is expected to be reached after the USO has been turned on for a sufficiently long enough period of time such that the only significant aging mechanism is diffusion. The curvature observed for the six passes conducted after the USO was cycled off and back on in Aug, 1991 could be attributed to stress relief and migration of impurities.

During the first UsO-on cycle (Dec. 1989 to Aug. 1991), 76 passes of USO data were acquired. An aging model was removed from the estimated spacecraft transmitted frequencies for this period, so that the resulting residuals could be analyzed, and remaining error sources could be identified. The model removed was that of a combination logarithmic curve and a linear aging drift;

$$f_{S/C} = C_1 \log_e [C_2 (t - t_0) + 1] + C_3 + C_4 (t - t_0) \quad \text{for } t < t_b$$

$$f_{S/C} = C_5 + C_6 \, (t - t_b) \quad \text{for } t \geq t_b$$

where t_0 is the time tag of the first data point, and t_b is the time tag of the first data point of where the linear aging realm begins. C_1-C_6 are constant coefficients, which were estimated by least-squares analysis.

The initial attempt to fit this model over the data acquired during the first USO-on cycle, resulted in the residuals displayed in Fig. 21. A large systematic variation is evi dent for passes occurring shortly after the USO was powered on, suggesting that the model is insufficient for this period. The rms scatter of the residuals is about 48 rnHz with a χ^2_n of 272. Since the behavior of the USO is known to be complex during this period and not easily modeled (initial stabilization phenomena masks the aging behavior), the first. twelve passes were deleted, and the model was fit to the remaining 64 passes. The correspond ng post-fit residual plot of Fig. 22 displays significantly less scatter and no significant systemati c variation. The rrns residual scatter of this fit was 17 mHz with a χ^2_n of 35. It is believed that the 17 mHz variations are due to the random walk of the USO or mismodeling. In an attempt to identify any mismodeling, the post-fit residuals were examined against troposphere correction, spacecraft-earth-sun angle, elevation angle, spacecraft range, signal level (AGC), gravitational redshift correction, station ID, USO oven current (from telemetry), and spacecraft temperatures (from telemetry). No apparent correlations or trends were detected.

The 17 mHz rms scatter of the estimated flight frequencies about the aging model is consistent with the level of random walk inferred from extrapolating the pre-flight Al lan deviation measurements as 7" to a weekly time interval. However, a portion of the 17 mHz scatter coul d possibly be attributed to some yet. to be identified mismodeling.

The logarithmic time constant C_2^{-1} was estimated to be about 71 days. The turnover of the curve occurred 259 clays after initial turn-on. The slope of the linear aging region was estimated to be -1.50×10^{-7} Hz/see which is in agreement with the measured slope of the Voyager 2 USO (-1.28×10^{-7} klz/see) [8]. 'l'his translates to an aging rate over a one day period of -5.6×10^{-12}, which shows that the USO is drifting well below its specification of 5×10^{-11}/day [9].

In an attempt to verify when the uso had reached its linear aging realm, different subsets of the last. several passes prior to first turn-off in Fig. 20 were subjected to linear fits of frequency versus time. Initial fits of the last 31 passes prior to first turn-- off (90-262 to 91-154), and the last 21 passes (90-360 to 91-154) displayed a signature in the residuals with significant curvature. A linear fit. of the last 19 passes (91-006 to 91-154) showed no significant residual signature and yielded results consistent with the combination logarithmic/linear combination fit discussed previously. This implies that the Galileo Uso required a little over a year of operation time prior to reaching its linear aging realm.

It is preferred that once the USO is switched on, it is left on so that it is allowed to reach the linear aging realm where it should remain for the duration of the Galileo activities. The linear aging realm allows Use-referenced (one-way) Radio Science experiments such as the gravitational redshift experiment and planetary occultations to be accurately calibrated. Since August 1991, the USO was switched off and back on in support. of cooling turns as part of the effort to free the High Gain Antenna (HGA) stuck ribs (in conjunction with corresponding warming turns) . The USO and its heater were powered-off on Aug. 5, 1991 (91-217). There were six passes conducted after the USO was powered back on Aug. 16, 1991 (91-228). The estimated spacecraft transmitted frequencies for these passes display a smooth continuity in time (see Fig. 23). A simple four-parameter aging model was fit to these frequencies yielding a post-fit rms scatter of 3 mHz. Although the number of points and time period were insufficient to infer an accurate linear aging rate, this result suggests that the USO is behaving in a reasonable manner during this period. The USO was again turned off after this time period. If the USO had been allowed to remain on, it. was expected that not as long of a period would be required for it to reach its linear aging realm as was the case during the first data set (89-341 to 91-154). The Allan deviations appear consistent with those of the first on-off data set, although two of the passes have somewhat higher values.

G. Retrace

If the USO and its heater are turned off, and then turned back on, the crystal will oscillate at a different frequency which is difficult to predict. This phenomena known as "retrace" is defined as the nonrepeatability of the frequency vs. temperature characteristic at. a fixed temperature upon on-off cycling of the oscillator [7]. An example of "retrace" is the 12 HZ jump between passes on 91-154 and 91-247 (see Fig. 20). Between these passes, the USO and its oven were turned off for an eleven day period in Aug. 1991. Several mechanisms which can cause retrace include strain changes, changes in the quartz, oscillator circuitry changes, contamination redistribution in the crystal enclosure and apparent, hysteresis [7].

H. Assessment of Environmental Effects

The frequency of the USO can change due to variations in environmental parameters which include temperature, pressure, acceleration, magnetic field, and radiation. The crystal frequency is also dependent on the power level. See [7], [10] and [11] for discussions on the effects of the various phenomena on the behavior of crystal oscillator devices.

'l'he Galileo USO was designed to minimize the effects of magnetic fields. A worst case estimate of the magnetic field of the spacecraft in the environment of the USO found that the resulting fluctuations in frequency were expected to be negligible for the 10 to 1000 sec time intervals [12].

Since the USO is oven controlled so as to maintain a constant temperature, and the crystal temperature is designed to operate at an optimum point on the f vs 1' curve, noise due to temperature fluctuations is expected to be insignificant.

The majority of the USO passes were conducted during quiescent periods on the spacecraft when there was no scheduled dynamic activity. 'I'he few known exceptions of dynamic activity involved no net thrusts on the spacecraft. Acceleration effects on the spacecraft USO are therefore considered to be negligible.

It is assumed that in the deep space environment, changes due to atmospheric pressure and humidity are virtually nonexistent,. Pre-launch testing showed that the Galileo USO exhibited spikes of less than 1 mHz during changes in pressure [13].

Due to the high level of shielding, no charged particles are expected to hit the crystal during cruise. High energy particles are expected to be stopped by the lead shielding producing photons which could possibly hit the crystal (G. Wood, private communication) . The level of radiation reaching the crystal during the cruise phase is expected to cause negligible shifts in frequency. The USO frequency could however shift about 1 HZ during passage through the Jovian radiation belts [14].

VII. Conclusion

The Galileo USO appears to be healthy and functioning in a reasonable manner based on the analysis presented in this article. The evaluation of the Radio Science instrument will continue for the duration of the mission.

Acknowledgements

P. Eshe, R. Herrera and T. Horton of the Radio Science Support Team provided valuable support. The comments and discussions provided by R. Sydnor and G. Wood of JPL, and R. Filler of LABCOM, New Jersey were greatly appreciated. The authors would also like to thank the Galileo Flight Team and Galileo Navigation learn for their support. The NASA/Deep Space Network generated the data used in this analysis. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California institute of Technology, sponsered by the National Aeronautics and Space Administration.

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13. Gussner, A., "Summary of Galileo Ultra Stable Oscillator (USO) Testing", JPL IOM 3364-80-080, Aug. ?0, 1980.

14. Wood, G. E., "Radiation Testing of Ultra Stable Oscillator S/N 004", JPL IOM 3396-76-095, August 20, 1976.

Table 1. **Galileo** USO Pass Summary

YEAR	DOY	START HR:MN:SC	END HR:MN:SC	DSS ID	AGC (dBm)	S/C TRANSMITTED FREQ - 2294997000 (Hz)
89	341	21:34:22	23:27:59	14	-149.5	690.321
89	350	00:02:40	01:57:59	14	-142.4	696.287
89	360	22:35:42	00:00:59	14	-145.5	699.954
90	2	17:09:45	18:59:59	14	-149.0	701.425
90	9	17:37:22	19:26:08	14	-149.6	702.669
90	15	17:34:22	19:28:11	14	--153.1	703.597
90	19	16:10:46	17:57:50	14	-156.1	704.134
90	28	16:00:09	18:00:00	14	-154.3	705.128
90	32	15:33:51	17:29:59	14	-155.8	705.508
90	37	10:50:57	12:12:36	63	-155.0	705.895
90	44	03:00:00	05:19:59	43	-151.6	706.383
90	46	00:19:29	01:04:57	43	-154.3	706.523
90	49	19:44:31	21:22:29	43	-153.9	706.855
90	56	02:10:12	03:26:48	43	-157.4	707.295
90	58	23:08:28	01:01:01	43	-158.5	707.457
90	61	00:17:51	01:55:53	43	-162.2	707.586
90	68	02:12:12	03:42:02	43	-159.5	707.987
90	76	02:19:06	03:28:03	43	-165.0	708.376
90	78	00:41:32	02:27:47	43	-166.5	708.452
90	83	19:13:51	20:56:11	43	-167.5	708.708
90	89	00:09:38	02:03:16	43	-166.8	708.888
90	97	22:18:28	23:55:22	43	-165.3	709.205
90	104	22:14:52	23:56:39	43	-167.6	709.422
90	110	00:47:05	02:26:45	43	-168.0	709.570
90	113	20:46:51	22:01:00	43	-169.0	709.671
90	121	23:21:02	00:57:56	43	-166.5	709.875
90	128	09:26:40	11:04:42	63	-168.3	710.014
90	136	23:22:03	01:16:30	43	-167.0	710.111
90	139	19:55:00	21:48:51	43	-166.9	710.166
90	149	19:17:45	21:02:08	43	-165.0	710.337
90	155	19:18:09	19:45:01	43	-165.7	710.395
90	162	18:14:46	19:43:47	14	-166.6	710.457
90	172	15:18:15	17:04:29	14	-164.8	710.566
90	176	16:19:35	18:05:46	14	-165.7	710.587
90	183	18:20:15	20:07:25	43	-165.6	710.634
90	193	14:48:37	16:34:51	14	-162.8	710.704
90	197	18:19:45	20:02:33	43	-165.0	710.720
90	206	21:17:32	23:00:05	43	-165.3	7)0.737
90	213	21:12:49	22:03:33	43	-165.6	710.769
90	221	20:43:23	22:29:37	43	-163.7	710.778
90	228	18:14:37	19:59:44	43	-162.8	710.775
90	233	15:17:38	17:03:53	14	-168.1	710.785
90	243	19:44:31	21:24:40	43	-165.5	710.764
90	250	01:41:02	02:45:10	63	-162.7	710.757
90	253	19:13:26	20:55:34	43	-161.1	710.735
90	262	19:26:55	21:11:16	43	-160.5	710.731
90	268	00:30:00	03:40:00	63	-162.5	'/10.706
90	274	18:56:25	20:43:34	43	-160.1	710.658
90	281	17:12:34	18:54:36	43	-156.9	710.612
90	303	01:44:22	03:23:19	63	-153.0	710.495
90	312	01:16:55	02:57:56	63	-148.5	710.432
90	32?1	03:18:28	04:58:11	63	-145.1	710.32?6
90	330	01:13:20	02:57:56	63	-145.0	710.271
90	345	02:14:52	03:42:02	42	-138.4	710.169

Table 1. Galileo USO Pass Summary (continued)

YEAR	DOY	START HR:MN:SC	END HR:MN:SC	DSS ID	AGC (dBm)	S/C TRANSMITTED FREQ - 2294997000 (Hz)
90	350	08:18:28	10:12:02	61	-147.7	710.115
90	360	17:09:14	18:57:41	43	-150.3	709.991
91	4	07:32:13	07:49:48	63	-149.4	709.922
91	6	18:01:47	19:58:45	43	-149.1	709.885
91	14	16:55:11	18:46:30	43	-152.5	709.792
91	16	17:04:22	18:59:59	43	-151.3	709.769
91	19	16:05:14	17:59:59	43	-152.5	709.743
91	21	18:04:52	19:58:57	43	-153.1	709.709
91	26	16:07:05	17:50:51	43	-154.8	709.657
91	29	06:07:42	07:58:54	63	-156.1	709.638
91	33	15:58:12	17:43:56	43	-158.1	709.577
91	36	06:07:11	07:58:50	63	-162.6	709.548
91	39	06:05:08	08:01:13	63	-160.9	709.507
91	43	15:05:08	16:59:59	43	-162.2	709.459
91	49	21:21:14	23:13:13	43	-160.6	709.370
91	55	15:35:23	17:30:30	43	-160.7	709.300
91	64	14:05:14	16:02:30	43	-158.6	709.173
91	73	16:23:17	18:13:59	43	-160.2	709.068
91	81	15:08:37	17:02:30	43	-155.4	708.929
91	109	19:02:38	20:45:14	43	-155.4	708.563
91	141	00:02:40	01:59:52	63	-157.6	708.161
91	154	23:04:06	00:59:41	61	-164.6	707.997
91	247	16:39:14	18:23:50	63	-167.5	696.304
91	259	21:28:12	23:11:46	14	-164.8	696.556
91	275	00:59:23	02:43:34	43	-165.9	696.678
91	292	15:15:11	17:00:01	63	-168.2	696.728
91	318	03:54:25	05:29:56	43	-168.1	696.772
91	334	20:41:17	22:10:45	14	-165.9	696.769

Table 2. Summary of Galileo USO **Allan** Deviations

Time Interval (sec)	Measured Flight $\times 10^{12}$	Measured Pre-launch $\times 10^{12}$
1	29.4 ± 1.1	0.56
10	3.93 ± 0.17	0.56
100	0.90 ± 0.03	1.1
1000	0.71 ± 0.03	0.68

Note: Uncertainties are errors in the mean.

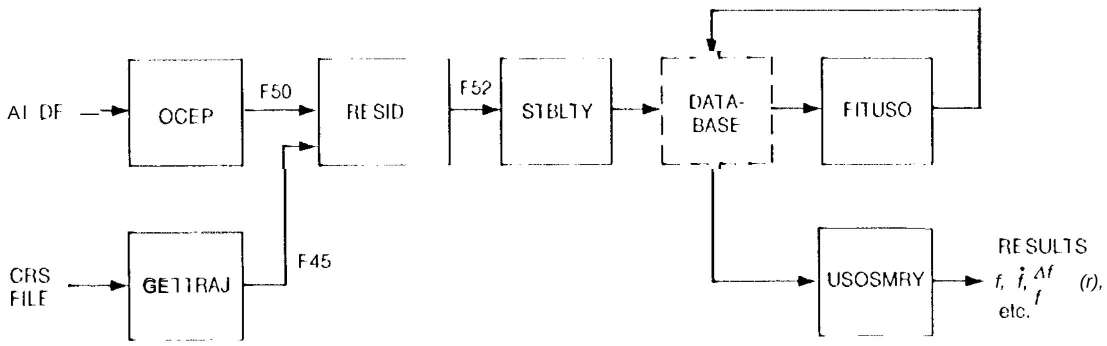


Fig. 1. STBLTY program-set block diagram.

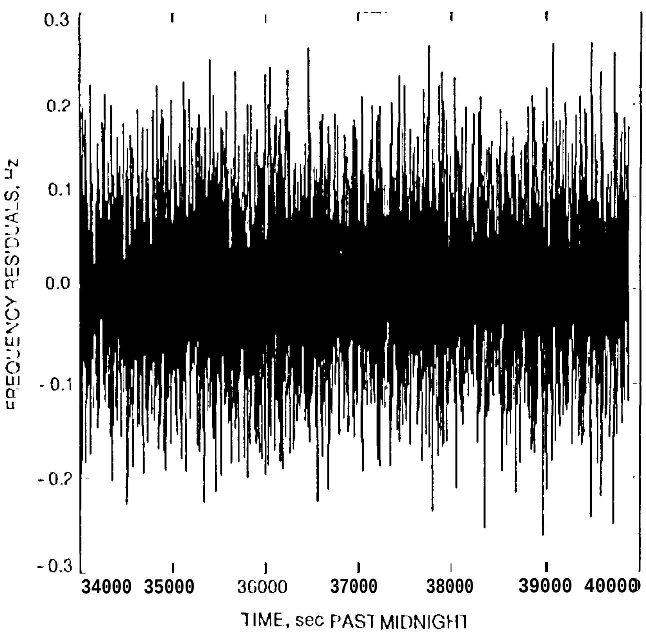


Fig. 2. Frequency residuals of sampled l/see Doppler for the USO pass of May 8, 1990.

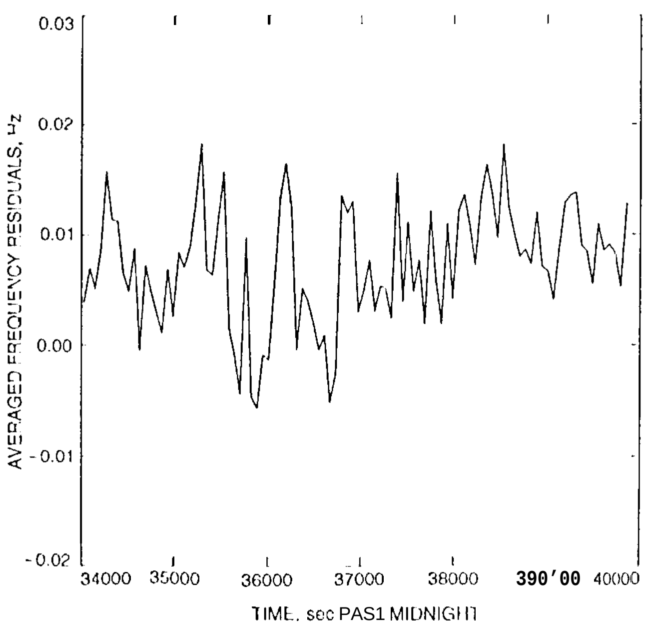
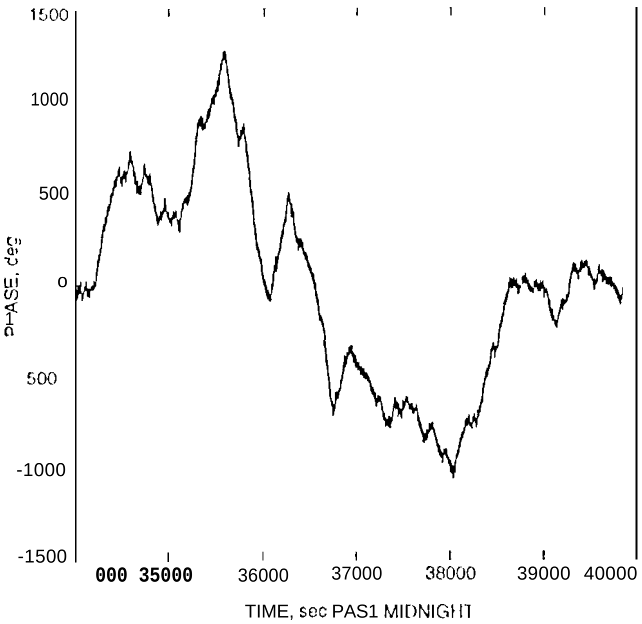


Fig. 3. Frequency residuals averaged every 60 sec for the USO pass of May 8, 1990,



Fig, 4. Phase reconstructed from frequency residuals for the USO pass of May 8, 1990.

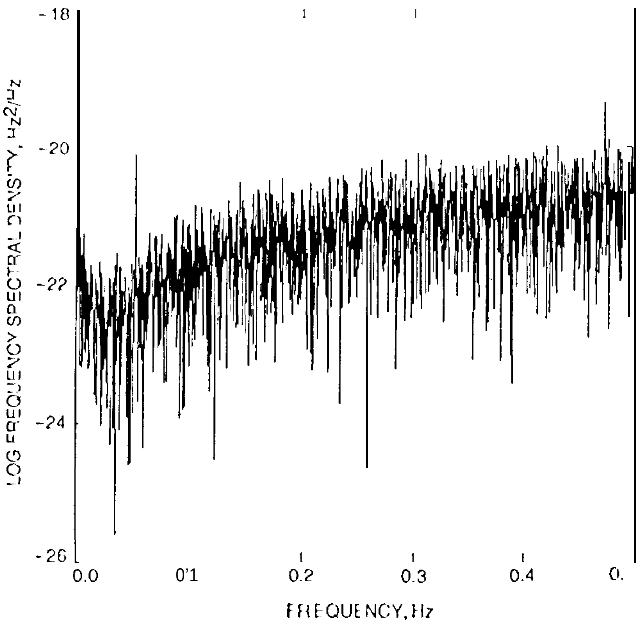


Fig. 6. Log of frequency spectral density of frequency residuals for the USO pass of May 8, 1990.

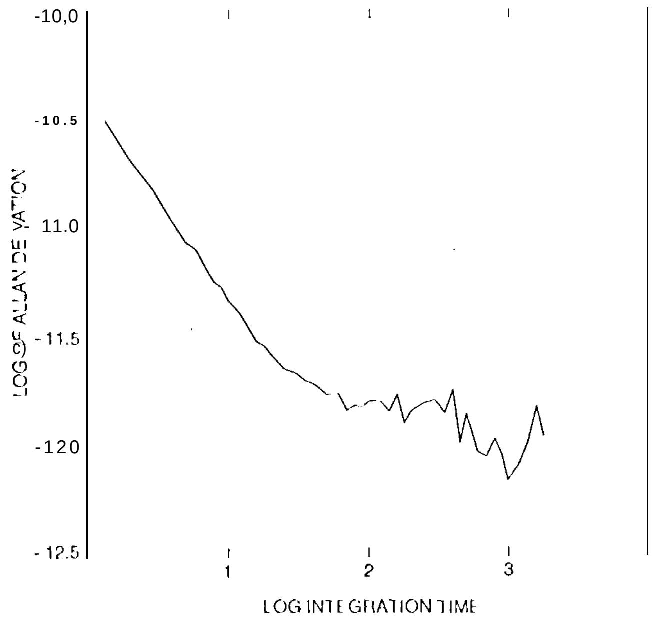


Fig. 5. **Log of Allan deviation of frequency residuals for the USO pass of May 8, 1990.**

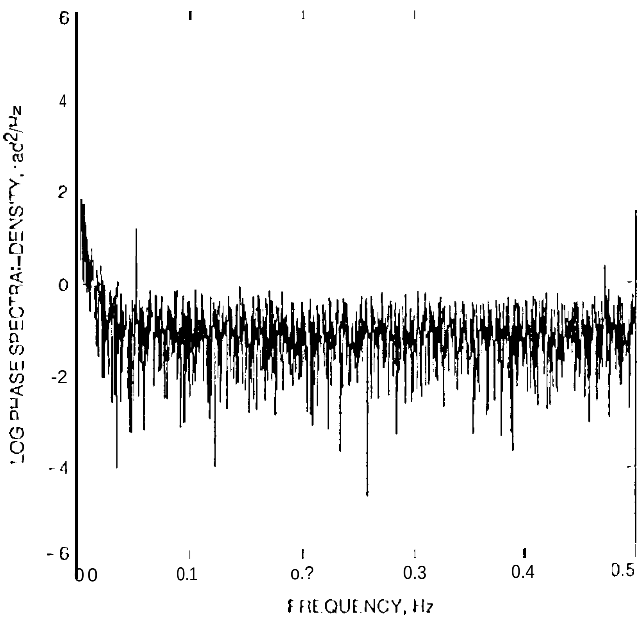


Fig. 7. Log of phase spectral density of frequency residuals for the USO pass of May 8, 1990.

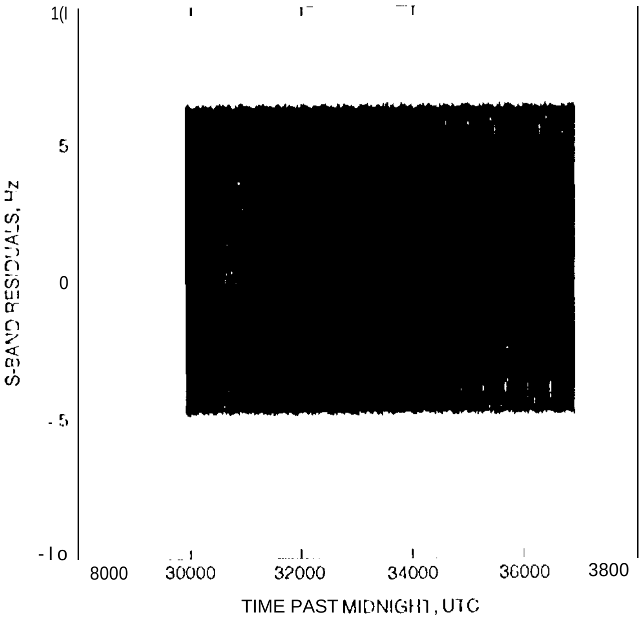


Fig. 8. Frequency residuals of sampled l/see Doppler for USO pass of December 16, 1990, where LGA-2 was the spacecraft antenna.

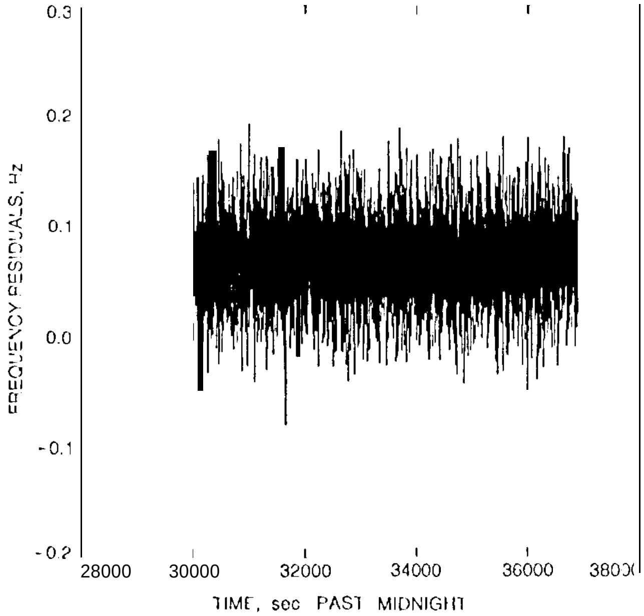


Fig. 10. Frequency residuals after removing the sinusoid fit from residuals displayed in Fig. 8 for USO pass of December 16, 1990, where LGA-2 was tho spacecraft antenna.

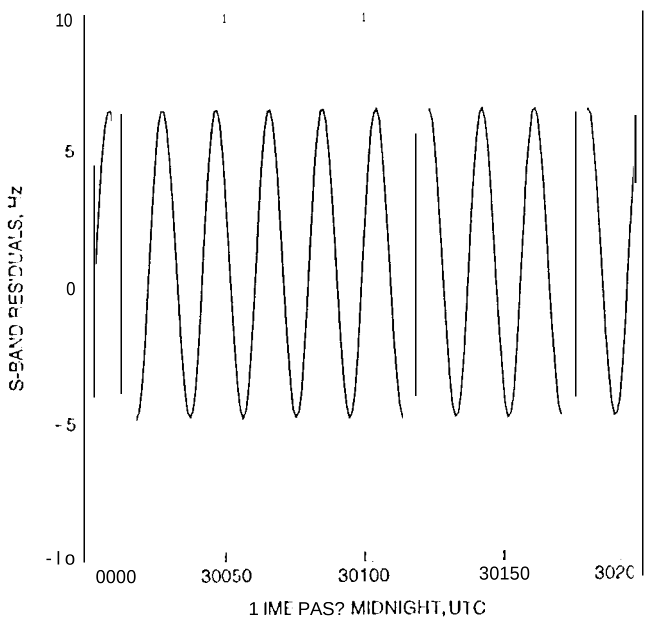


Fig. 9. Selected 200-sec period of frequency residuals of sampled l/see Doppler for USO pass of December 16, 1990, whore LGA-2 was tho spacecraft antenna.

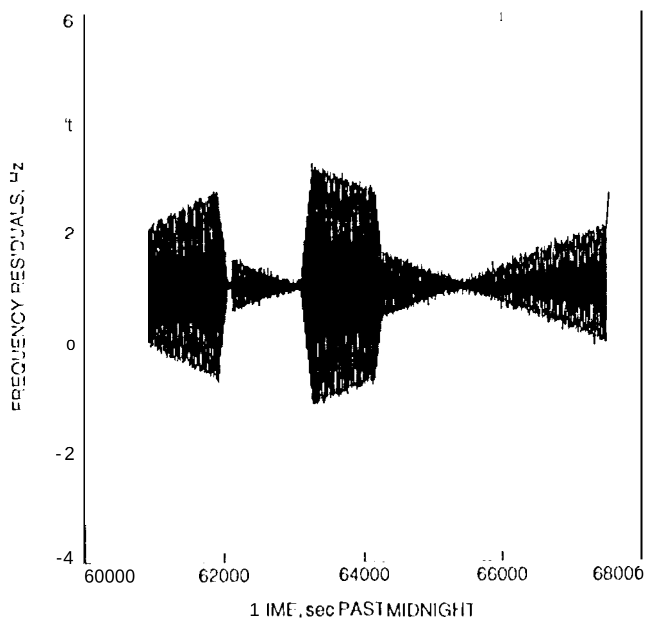


Fig. 11. Frequency residuals of sampled 1/sec Doppler for the USO pass of January 14, 1991, where LGA-2 was the signal source and dynamic motion occurred on board the spacecraft.

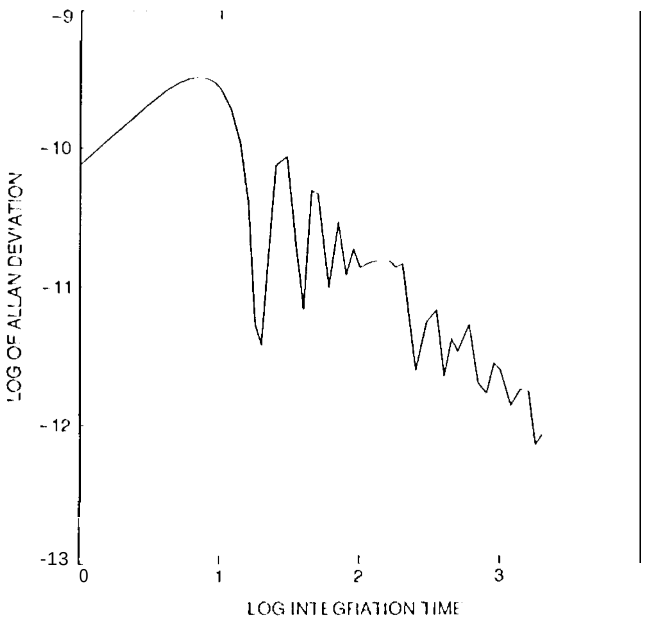


Fig. 12. Log of Allan deviation of frequency residuals of Fig. 11.

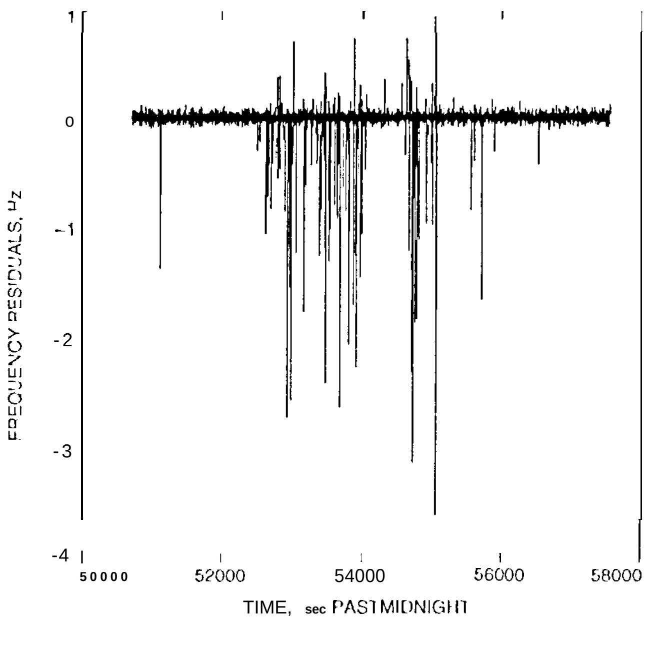


Fig. 13. Frequency residuals of the USO pass of March 5, 1991, where solar activity was known to have occurred.

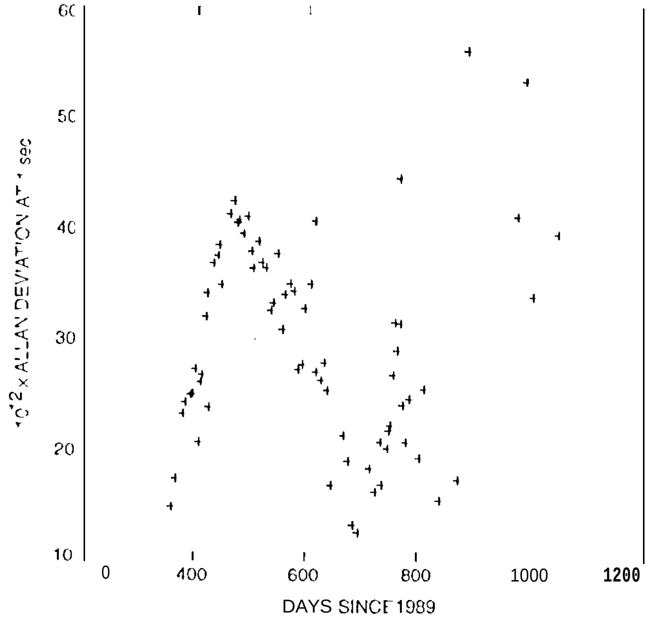


Fig. 14, Allan deviations at 1 sec for 73 USO passes (outliers have been removed).

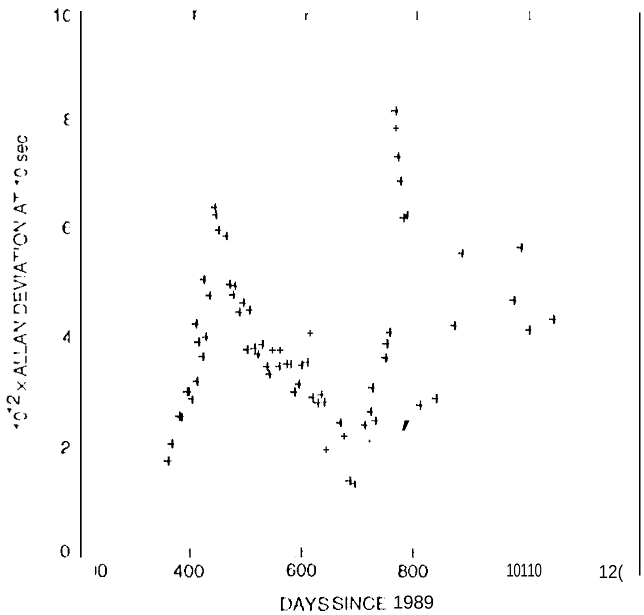


Fig. 15. Allan deviations at 10 sec for 73 USO passes (outliers have been removed).

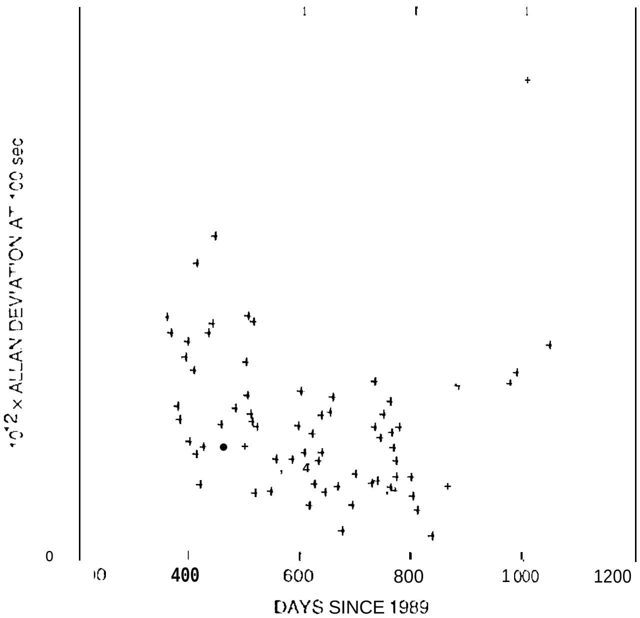


Fig. 16. Allan deviations al 100 sec for 73 USO passes (outliers have been removed).

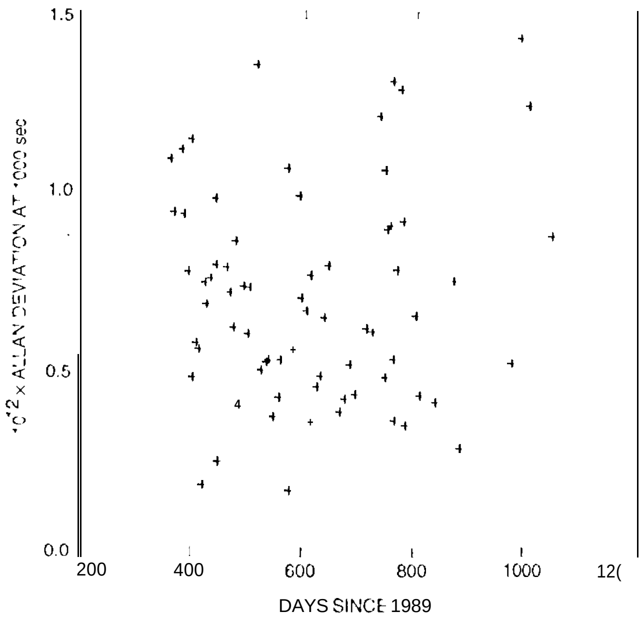


Fig. 17. Al lan deviations at 1000 sec for 70 USO passes (outliers have been removed).

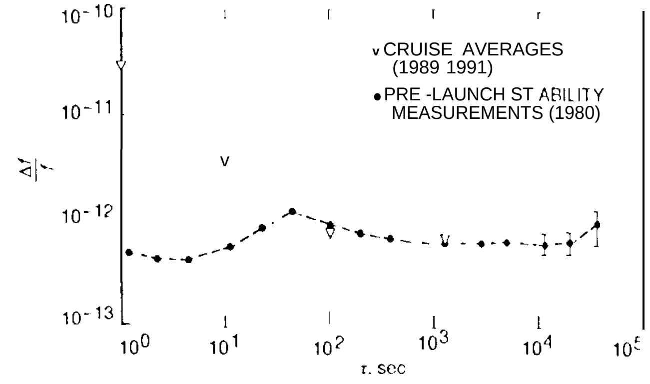


Fig. 18. In-flight USO-pass Allan-deviation measurement averages for 1, 10, 100 and 1000 sec superimposed with pre-flight Allan deviation measurements.

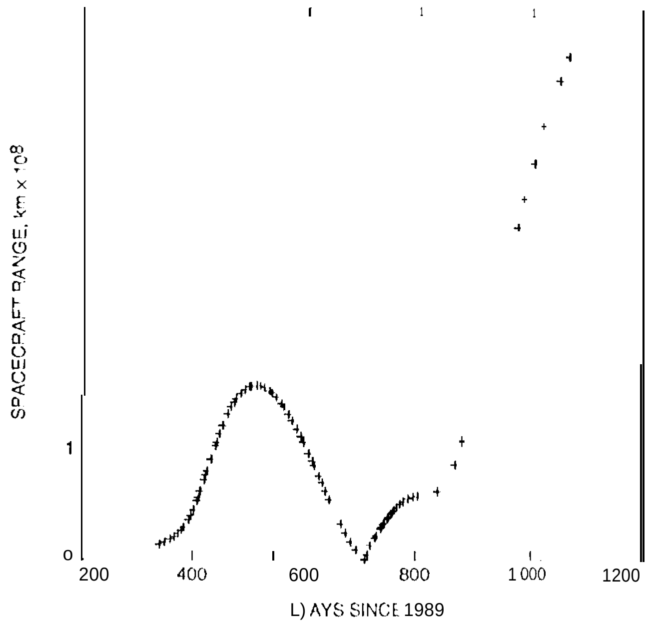


Fig. 19. Spacecraft range for each USO pass. Launch occurred at day 291; the dip at 707 days after 1989.0 was the Earth 1 flyby.

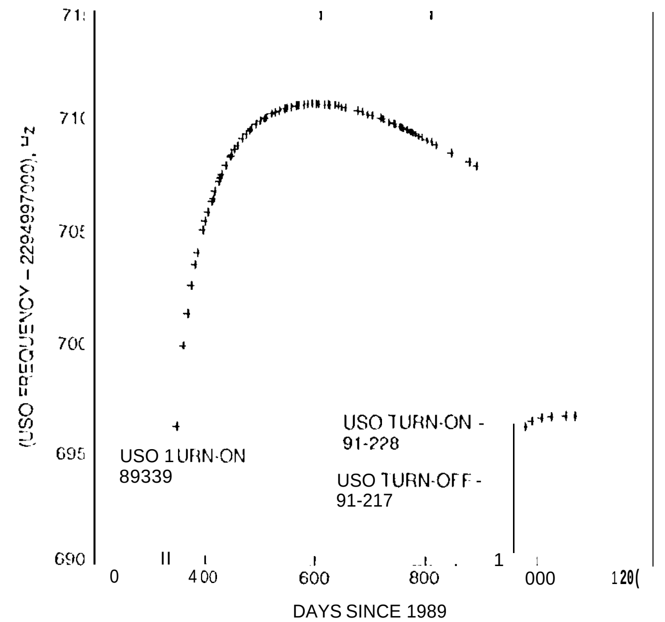


Fig. 20. Estimated spacecraft transmitted frequencies for all 82 USO passes as determined by STBLTY.

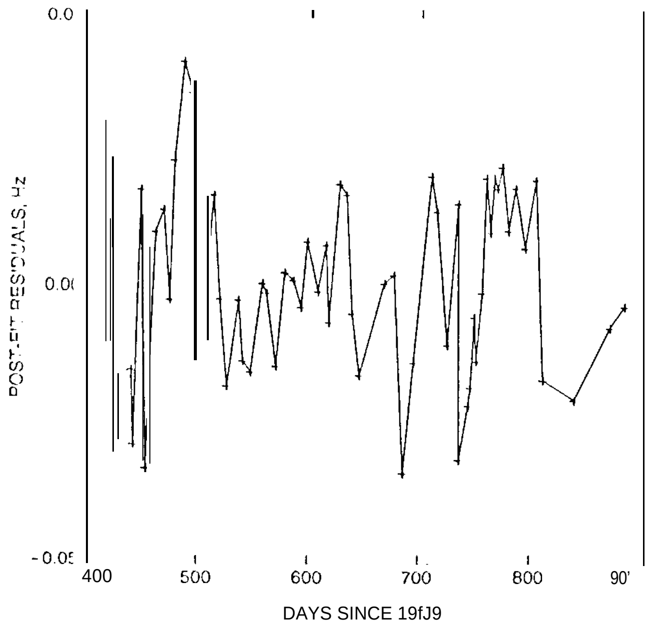


Fig. 22, Post-fit residuals of estimated spacecraft transmitted frequencies of the first USO on-off cycle for 64 passes (first 12 removed) after fitting and removing an aging model

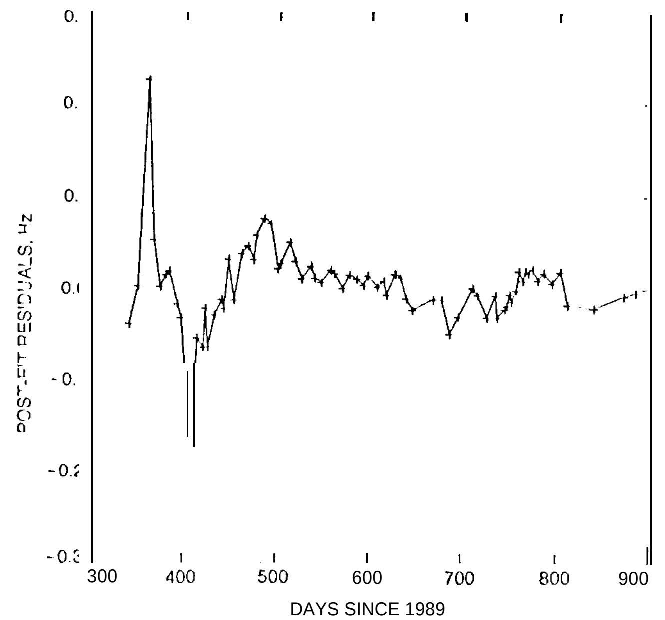


Fig. 21. Post-fit residuals of estimated spacecraft transmitted frequencies of the first USO on-off cycle for all 76 passes after fitting and removing an aging model.

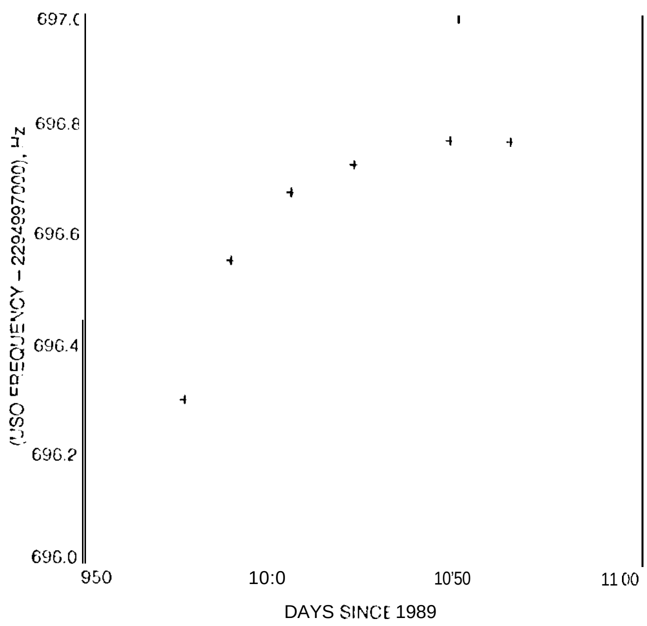


Fig. 23. Estimated spacecraft transmitted frequencies of 6 US() passes conducted after the first USO on-off cycle.